USESO 2023

Training Camp Exam

Free-response

Instructions:

- Section II consists of 5 multipart questions that further assess geoscience knowledge in the form of mostly free-response questions.
- You have 2 hours and 15 minutes.
- Any type of calculator is allowed.
- Participating in this exam is agreement to our academic integrity policy.

Problem 1

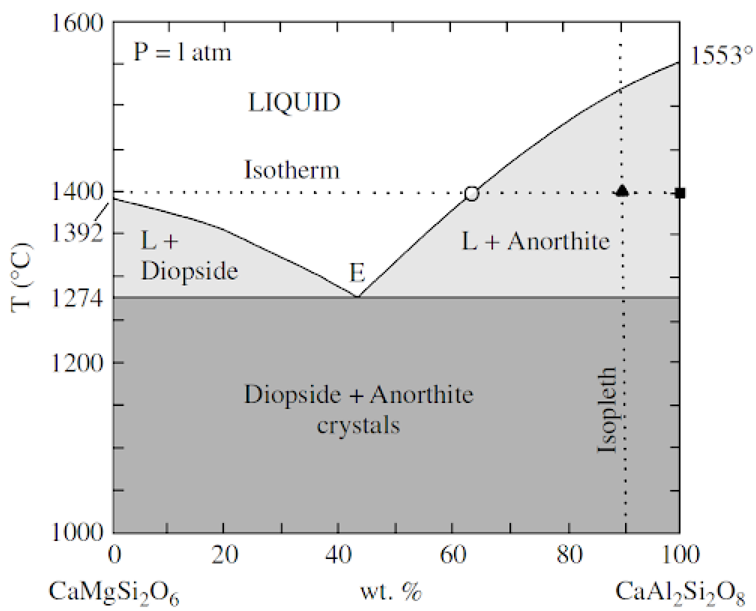
Question	1	2	Total
Points	9	11	20 (20%)

Naturally, Ca- and Mg-containing minerals can undergo carbonation reactions to produce carbonate minerals like calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), or magnesite ($MgCO_3$). There is some interest in artificial carbonation of igneous rocks as a method of carbon sequestration. Here we will explore some of the basic science related to this field.

1. (a) (3 points) Most of the basalt on the Earth's surface are flood basalts. In two or three sentences, briefly explain the origin of continental flood basalts. In your answer, characterize volcanism as either effusive or explosive and briefly describe the mechanism of formation for volcanoes that produce flood basalts.

Solution: Flood basalts are typically formed by effusive eruptions from the largest sources of magma, typically continental hotspots. Large quantities of undifferentiated magma pour through the crust and solidify at the surface to create mafic extrusive igneous rock.

(b) Diopside ($CaMgSi_2O_6$) and anorthite ($CaAl_2Si_2O_8$) are two relatively common minerals in basalt. Consider the composition-temperature phase diagram of diopside and anorthite:



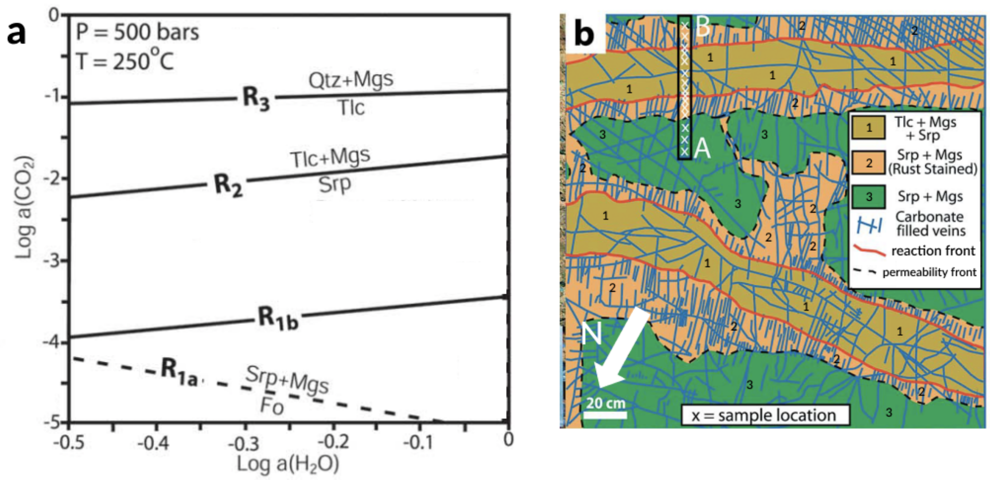
i. (4 points) Consider a mixture with bulk composition and temperature plotted by the triangle mark. What are the composition of the solid and liquid phases? Estimate the fraction of solid and liquid phases in the mixture. (*Detailed work is not needed, a description of your calculation is sufficient*)

Solution: The composition of the solid and liquid phases can be found at the bounds of the L + Anorthite section at the given temperature. The solid phase is represented by the square at 100% anorthite, while the liquid phase is represented by the circle at about 63% anorthite and 37% diopside.
The mixture is composed of about 27% liquid magma and 73% solid anorthite. According to the lever rule, the relative concentrations of the two phases present in the melt are inversely proportional to the distance between their compositions and the mixture's bulk composition. Since the bulk composition is separated by 10% from the solid and 27% from the liquid, there will be about 2.7 times as much anorthite as liquid.

ii. (2 points) As that mixture cools, suppose some of the solid crystals no longer remain in chemical equilibrium with the rest of the mixture. Describe briefly what occurs to the bulk composition of the mixture. What igneous differentiation process does this model?

> **Solution:** This models the process of fractional crystallization, in which solid material is continuously removed from the melt as it crystallizes. As this solid is removed from the melt, the bulk composition shifts away from the solid and towards the liquid, i.e. away from anorthite and towards diopside.

Studies have been done on the natural carbonation of serpentinite, which forms from the hydrothermal alteration of basalt. One such study showed that the carbonation of serpentinite occurs via a pathway of four reactions, labeled here R_{1a}, R_{1b}, R_2, and R_3.



(a) shows the stability of various mineral phases present in serpentinite as a function of the chemical activity of CO_2 and H_2O. For our purposes, consider activity to be a dimensionless quantity that represents an "effective concentration". **(b)** shows a 2 by 2 meter outcrop that has been mapped and labeled with mineral assemblages.

Key for mineral abbreviations

Srp	serpentine group
Mgs	magnesite
Tlc	talc
Qtz	quartz
Fo	forsterite

2. (a) (2 points) Which reaction occurred within the tan conduits (labeled 1) but did not occur in the green matrix (labeled 3) that distinguishes the tan mineral assemblage from that of the green mineral assemblage?

   A. R_{1a}

   B. R_{1b}

   C. R_2

   D. R_3

> **Solution:** Both the tan and green mineral assemblages include Srp and Mgs, while the tan assemblage also includes Tlc. The only reaction that could form Tlc from Srp or Mgs is reaction R_2.

(b) (6 points) Calculations show that each of the four carbonation reactions proceed with an increase in solid volume. Considering how these reactions *physically* take place (i.e., how is CO_2 transported into rock so that carbonation can actually occur?), explain how this increase in volume can feed back on reaction rates.

> **Solution:** Carbonation reactions occur as CO_2-containing fluid infiltrates the rock through joints and fractures. This infiltration causes reactions that expand the volume of the solid as described in the question. An increase in volume would likely increase porosity and permeability, allowing more CO_2-containing fluid to enter the rock and cause a faster reaction. This would likely result in a positive feedback loop.

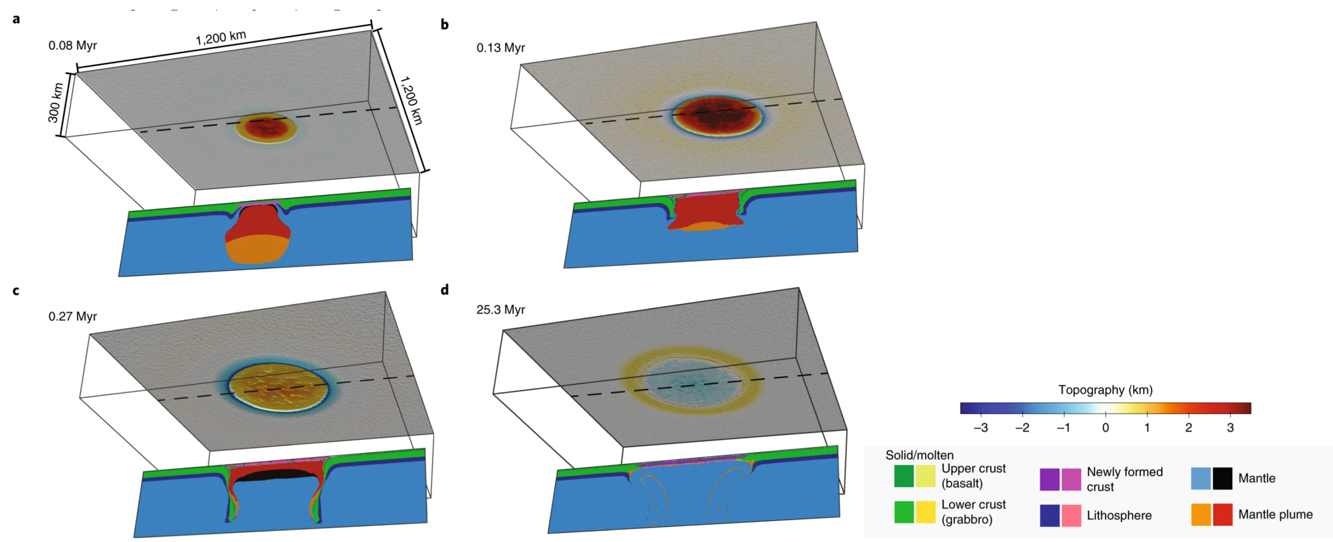
(c) (3 points) In Figure (b), the carbonate-filled veins tend to have a preferred orientation, perpendicular to the conduits where carbonation has taken place. What does this suggest about the mechanical stresses that occurred during carbonation? In your answer, indicate whether the stress was compressive or tensile, and the primary axis of stress (note that north is given by the white arrow in the bottom left).

> **Solution:** Veins would only open up within the rock due to tensile stress, likely due to expansion caused by carbonation reactions. These fractures would likely form perpendicular to the direction of stress as different sections of rock are pulled away from each other. Since the preferred fracture orientation is north-south, the direction of stress was likely east-west.

Problem 2

Question	1	2	3	4	5	Total
Points	4	3	4	2	7	20 (20%)

Venus's surface contains dozens of *coronae*, circular regions of highly deformed and fractured crust. The following figure depicts a proposed method of formation in four steps (chronologically from a to d) in which a mantle plume rises and deforms part of the crust. The image includes both surface topography and a mantle cross-section for each stage.



1. (a) (2 points) The process depicted in stages (a) and (b) is most similar to which of the following tectonic processes on Earth?

   A. Seafloor spreading

   B. Alpine-type mountain building

   C. Fault-block mountain formation

   D. Batholith formation

   Solution: In stages (a) and (b), an upwelling mantle plume pushes the crust up and apart. This is the same process that occurs during the formation of mid-ocean ridges, where mantle upwelling pushes the region upward and causes the crust to move away from the ridge.

   (b) (2 points) This process is different on Venus because the Venusian crust is not split into tectonic plates despite its magmatic activity. Explain how one difference between Venus and Earth contributes to Venus's lack of tectonic plates.

   Solution: Multiple answers accepted. This difference may be due to Venus's elevated surface temperature, as the crust is more ductile at high temperatures and may be more resistant to the brittle breaking necessary for plate tectonics. This may also be due to Venus's lack of surface water; it has been suggested that water serves as a lubricant necessary for tectonic plate formation.

2. (3 points) In stage (c), part of the lower crust delaminates from the upper crust and sinks into the mantle. This sinking does not immediately occur because the crust is slightly less dense than the mantle. Briefly explain why

the crust eventually becomes dense enough to sink.

Solution: The high pressure of the mantle metamorphoses any sinking crust, compressing it and causing it to release volatiles. This compression results in an increase in crustal density, making it somewhat denser than the warmer surrounding mantle.

3. In stage (d), the crust returns to a stable state after a long time. Notice that the center and rim have inverted since stage (c), with the center sinking and the rim rising.

   (a) (2 points) Briefly account for the sinking of the center of the corona.

   Solution: The initial rise of the center is due to the upward pressure from rising mantle material. When the mantle plume has dissipated, that pressure disappears, causing it to sink to near its original height. It also returns to a lower height because the up-and-out motion of the mantle plume stretches and thins the crust, causing it to be less buoyant and rise lower above the mantle.

   (b) (2 points) Briefly account for the rise of the outer rim of the corona.

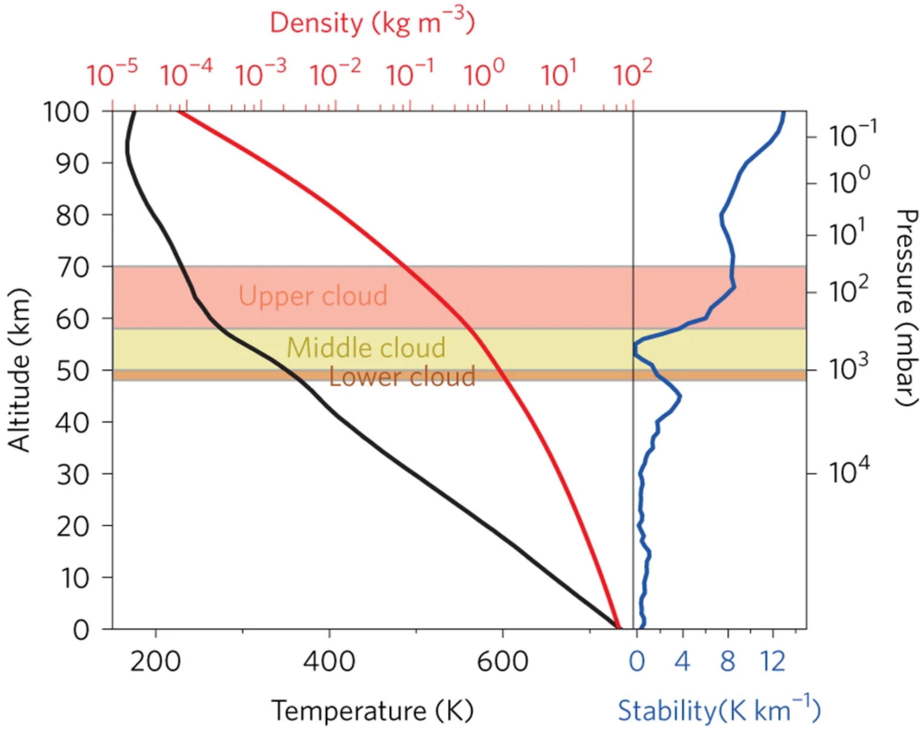
   Solution: The sinking lithospheric material drags down on the outer rim of the corona, since its sinking motion means it is denser than the mantle. Once delamination occurs, this downward pull no longer exists, allowing the rim to rise back up.

The following table gives the concentrations of the most common gases in the Venusian atmosphere.

Gas	Concentration
Carbon dioxide	96.5%
Nitrogen	3.5%
Sulfur dioxide	150 ppm

4. (2 points) Tectonic activity at coronae significantly impacts Venus's atmospheric composition. Briefly explain how this tectonic activity contributes to the unusually high concentrations of CO_2 and SO_2 in Venus's atmosphere.

Solution: CO_2 and SO_2 are both volcanic gases. Since coronae thin Venus's crust and lie above rising magma, they typically have more magmatic and volcanic activity than more static parts of the crust. As magma comes to the surface, the lower pressure causes dissolved gases in the magma to be released into the atmosphere.



5. Venus has an enormously strong greenhouse effect because of the high concentrations of CO_2 in its atmosphere and the insulating effect of sulfuric acid clouds. These thick clouds trap most outgoing radiation and absorb a small percentage of incoming radiation.

(a) (4 points) Venus's atmosphere absorbs more energy from the Sun at its equator than at its poles. Most of this energy is absorbed by the upper cloud layer rather than the Venusian surface. How does this differential energy absorption affect the stability of Venus's cloud layer and lower atmosphere at the equator compared to the poles?

Solution: Venus's atmosphere is more stable at the equator. Hotter air lying below colder air is generally unstable, as hot air tends to be less dense and rise above colder air. Although air in the atmosphere is stratified by density, changes in temperature can cause changes to density that make it easier or harder for warm air to rise. At the equator, absorbed insolation causes the upper cloud layer to warm, reducing the environmental lapse rate and reducing the unstable negative temperature gradient. At the poles, upper air cools as it radiates heat into space, causing it to become more dense and allow warmer air beneath it to rise.

(b) (3 points) Does this effect strengthen or weaken global Hadley circulation on Venus? Explain.

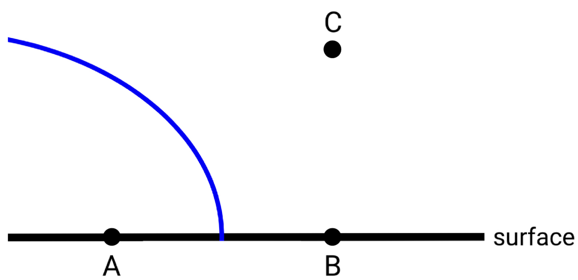
Solution: This effect weakens global circulation. This circulation is primarily driven by the rising of warm air at the equator, caused by insolation reaching the ground and warming surface air. When upper clouds absorb this radiation, it reduces the temperature gradient of the air below the clouds, making it more difficult for equatorial air to rise. While upper air does sink at the poles, surface air rises to replace it; it doesn't create global circulation because there's less equatorial movement to balance it.

Problem 3

Question	1	2	3	4	Total
Points	6	6	3	5	20 (20%)

This question explores various aspects of and features associated with mid-latitude cyclones and storms. For this question, assume that all weather systems are in the Northern Hemisphere.

1. The structure of fronts in mid-latitude cyclones can be diagnosed by the *potential temperature* θ, which is defined as the temperature that a parcel would attain if moved dry adiabatically (9.8 K/km) to 1000 hPa (approx same as surface pressure). Consider the following simplified cross-section of a cold front (the boundary is marked blue):



(a) (2 points) Assuming that the environmental lapse rate < 9.8 K/km everywhere, rank the letters in order from lowest to highest *potential* temperature θ. Use < or = between each letter.

> **Solution:** A < B < C. A and B are both at the surface, so their actual temperatures are close to θ. Since B is in the warm air mass or warm sector of the front, it has a higher θ than A. It is also given that the environmental lapse rate is less than 9.8 K/km. If C were brought down to the surface at 9.8 K/km, it would be warmer than B, so it has a higher θ than B.

(b) (2 points) The buoyancy frequency N^2 over some small range in height Δz is proportional to (static) stability in the atmosphere, given by the formula

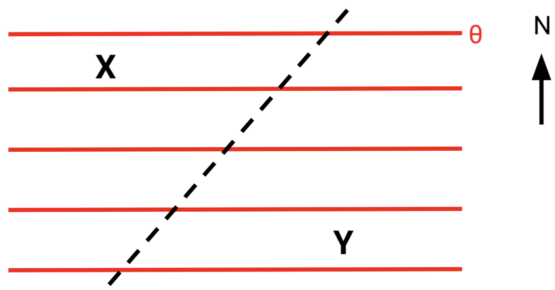
$$N^2 \approx g \frac{\Delta \ln \theta}{\Delta z}$$

where g is the gravitational acceleration and z is height.

Based on the relative stability of air masses, on which side of the cold front in the diagram (A or B) is the vertical gradient of θ greater?

> **Solution:** The side with point A has the greater gradient. The cold air mass overlying point A will be more stable. Because greater stability is linked to a greater change in θ, there will be a greater gradient of θ above point A.

(c) (2 points) Frontogenesis occurs when the potential temperature gradient becomes tighter with time. Consider the following horizontal map view of surface potential temperature (red contours), the position of a future front (dashed line), and the location of two pressure systems X and Y:



Identify each pressure system X and Y that most typically leads to frontogenesis.

A. X - low, Y - low

B. X - low, Y - high

C. X - high, Y - high

D. X - high, Y - low

Solution: Both X and Y are high pressure systems. X advects colder (lower θ) air southward, and Y advects warmer (higher θ) air northward, causing an increased θ gradient.

2. Although mid-latitude flows are usually close to geostrophic balance, it is not always a valid assumption throughout the atmosphere.

(a) (4 points) Identify the **two** cases below for which geostrophic balance does **not** approximate the flow. Briefly justify your answer for each choice. *Merely stating the forces behind geostrophic balance is* ***not*** *sufficient justification; consider which forces can/can't be neglected.*

- Flow near the equator
- Flow near the poles
- Flow within the planetary boundary layer (PBL)
- Slow flow aloft outside of jet streams

Solution: Flow near the equator would not be geostrophic because the Coriolis force is negligible and cannot balance the pressure gradient force (PGF). Flow within the PBL would also not be geostrophic because friction disrupts the balance between the Coriolis force and the PGF. Also, flows within the PBL are primarily turbulent and occur at small scales, so the Coriolis force is minimal or negligible.

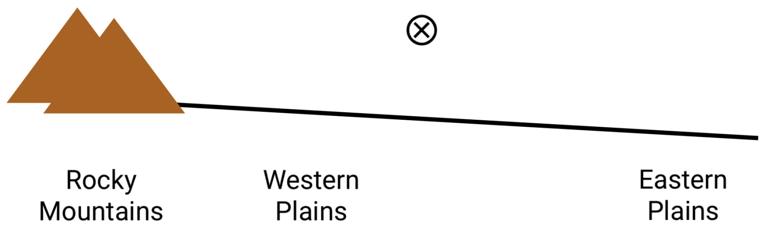
The Coriolis force strengthens with latitude and is not weak near the poles, so geostrophic balance holds for flow near the poles. Geostrophic balance also holds for weak winds aloft, in which case a weak PGF balances a weak Coriolis force (which depends on the wind velocity also).

(b) (2 points) Geostrophic balance also does not hold for aloft flows around closed lows, which are detached from the jet stream and are nearly symmetric. Identify the dominant force causing air aloft to accelerate around closed lows.

Solution: Pressure gradient force (PGF). In the Northern Hemisphere, the Coriolis force deflects winds towards the right. Since flow around lows is counterclockwise, there should be a net centripetal force inward; this is accomplished by a PGF greater in magnitude than the Coriolis force. (Note that this is a case of gradient wind.)

3. (3 points) Severe thunderstorms are relatively common in the Central Plains of the United States.

The nocturnal (nighttime) low-level jet (LLJ), which advects moist air via southerly winds, can sustain thunderstorms at night over the Central Plains. The Rocky Mountains and western Plains are at higher elevations than the eastern Plains, as shown in the figure below.

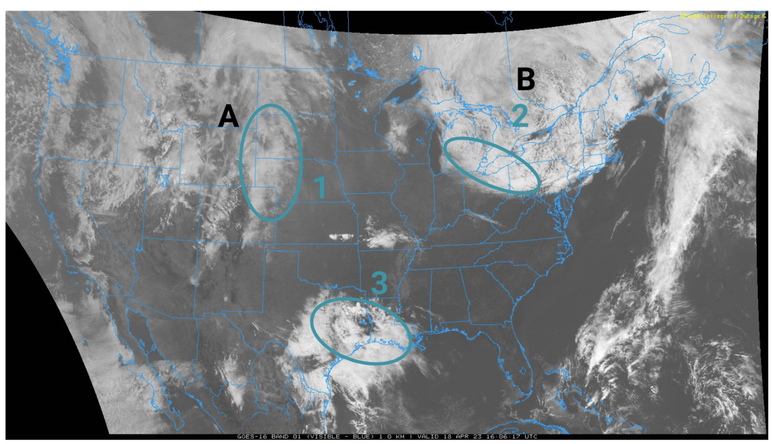


The circled cross indicates the LLJ is blowing into the page.

Explain how a west-to-east moisture gradient contributes to the development of the LLJ. In your answer, identify the direction in which the moisture gradient must point. *(Hint: consider how temperature is affected.)*

Solution: Increasing moisture in the eastward direction would favor a southerly LLJ. Moister air to the east leads to less efficient radiational cooling (or less adiabatic cooling) in the east than the west, creating a temperature gradient with warmer air to the east. This creates a westward PGF aloft and southerly winds.

4. Mid-latitude cyclones can also be a cause of severe thunderstorms. Shown below is a visible satellite image on April 18, 2023. A and B refer to different cyclones, and circled regions 1 to 3 correspond to different cloud regions.



(Image courtesy of Iowa State/NOAA)

(a) (3 points) Indicate whether each of the following statements is true or false.

i. A has a higher surface pressure than B.

ii. A is expected to weaken sooner than B.

iii. Of all the cloud regions, the clouds in Region 2 are most likely to be formed by frontal lifting.

Solution: From the images, A is likely a developing wave cyclone. B is a mature mid-latitude cyclone with a well-defined cold front and a comma-shaped cloud pattern, so B likely has the lower surface pressure - I is true. Based on the typical life cycle of mid-latitude cyclones, A is expected to strengthen. B is a mature cyclone and is expected to begin weakening and dissipating soon, as the low becomes occluded and the source of warm air is cut off from the center - II is false. Based on the satellite image, both the cold and warm fronts associated with B are likely well to the east of region 2, and the occluded front is likely to the east of B, where the cold front catches up to the warm front - III is false. Region 1 would be most likely candidate for clouds formed by frontal lifting instead.

(b) (2 points) A day later, tornadic supercell thunderstorms affected parts of the Central Plains, including Oklahoma, with strong wind shear observed. Briefly describe one reason that wind shear helped to support supercell thunderstorms.

Solution: The presence of wind shear causes updrafts and downdrafts to be tilted and remain separated, allowing a continuous supply of warm, moist air to the storm. Wind shear also supports rotating updrafts and mesocyclone development, a key feature of supercells.

Problem 4

Question	1	2	Total
Points	10	10	20 (20 %)

The fact that Earth's surface temperature and pressure allows liquid water at its surface is one of the defining features of our planet that allows it to support life. In this question, we will explore various factors that influence Earth's surface temperature and apply it in the TRAPPIST-1 planetary system.

1. The energy radiated by an object can be modeled by the Stefan-Boltzmann law:

$$P = A\varepsilon\sigma T^4$$

where P is the power output, A is the surface area of the object, ε is a dimensionless number called emissivity, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant, and T is the absolute temperature.

(a) (1 point) We will assume the Sun is a perfect blackbody with a radius of 6.96×10^8 m and surface temperature of 5772 K. Find the power output of the Sun in W. You may use $P = 5.00 \times 10^{26}$ W for following parts if you do not obtain an answer to this part.

Solution: A is equal to $4\pi r^2$, the surface area of the sphere, because the Sun is spherical. Since we assume the Sun is a blackbody, it must have $\varepsilon = 1$. Since R, σ, and T are known, we can plug these values into the equation to get $P = 3.83 \times 10^{26}$ W.

(b) A planet's effective temperature is the temperature that it would have if it were a blackbody radiating away all incident energy absorbed from its parent star.

i. (2 points) Let P denote the power outputted by the Sun. First, write an algebraic expression for the radiant flux density ρ (defined as radiant power per unit area) at a distance r from the Sun.

Solution: The power is spread over a sphere of surface area $4\pi r^2$, so $\rho = \dfrac{P}{4\pi r^2}$.

ii. (2 points) Write an algebraic expression for the incident power P_{inci} (how much power Earth absorbs) in terms of P, r, the radius of the Earth R, and Earth's albedo α.

Solution: The fraction of reflected incident power is given by α, so the fraction of absorbed incident power is equal to $1 - \alpha$. The cross-sectional area of the region absorbing power from the Sun is given by πR^2. P_{inci} is equal to ρ times the absorbing area times the fraction of power absorbed:

$$P_{\text{inci}} = (1 - \alpha)\pi R^2 \rho = \frac{(1 - \alpha)R^2 P}{4r^2}$$

iii. (2 points) Solve algebraically for the effective temperature T_{eff} of the Earth by equating the incoming and outgoing power. Use $\varepsilon_{\text{Earth}}$ to denote the emissivity of Earth.

Solution: Energy balance tells us the incident power is equal to the power emitted by Earth:

$$P_{\text{inci}} = A\varepsilon_{\text{Earth}}\sigma T_{\text{eff}}^4$$

Substituting $4\pi R^2$ for A gives us the following equation:

$$\frac{(1-\alpha)R^2 P}{4r^2} = 4\pi R^2 \varepsilon_{\text{Earth}} \sigma T_{\text{eff}}^4$$

Solving for T_{eff} gives us the following equation:

$$T_{\text{eff}} = \left(\frac{(1-\alpha)P}{16\varepsilon_{\text{Earth}}\sigma\pi r^2} \right)^{1/4}$$

iv. (1 point) If you used the emissivity of the Earth's atmosphere, estimated to be around $\varepsilon_{\text{Earth}} = 0.96$, the temperature you would calculate would be far lower than the average surface temperature of the Earth (288 K, or 15°C). This is, of course, because we didn't account for the greenhouse effect. As a surrogate for this omission, we can let ε instead be an *effective* emissivity ε_{eff} to artificially parameterize the greenhouse effect. Give a physical explanation for why $\varepsilon_{\text{eff}} < \varepsilon_{\text{Earth}}$.

Solution: The greenhouse effect means that the outgoing radiation at the top of the atmosphere is less than the outgoing radiation at the surface. If we want to account for this effect, we would need to decrease ε to parameterize the effect of less outgoing radiation.

v. (2 points) Calculate the value for ε_{eff} needed to raise Earth's effective temperature T_{eff} to its current average surface temperature of 288 K. Use $\alpha = 0.3$, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}, and $r = 1.50 \times 10^{11}$ m = 1 AU.

Solution: Rearranging the expression in (iii) gives

$$\varepsilon = \frac{(1-\alpha)P}{16\pi r^2 \sigma T_{\text{eff}}^4}$$

and plugging in known numbers gives us $\varepsilon_{\text{eff}} = 0.6077$. (Using $P = 5.00 \times 10^{26}$ W gives $\varepsilon_{\text{eff}} = 0.793$.)

2. Applying these calculations to the TRAPPIST-1 system allows us to estimate a very rough estimate for its habitable zone.

(a) (3 points) The star TRAPPIST-1 has a luminosity (radiant power output) of about 5.5×10^{-4} solar luminosities. Assuming that the habitable zone is defined by distances from the star where liquid water can exist on a planet's surface, calculate the inner and outer radii of TRAPPIST-1's habitable zone, in AU. Use ε_{eff} that you calculated in 1b(v) to emulate a greenhouse effect, and use $\alpha = 0.3$ for an Earth-like surface. (Note: 0°C ≈ 273 K)

Solution: We rearrange the energy balance equation to get

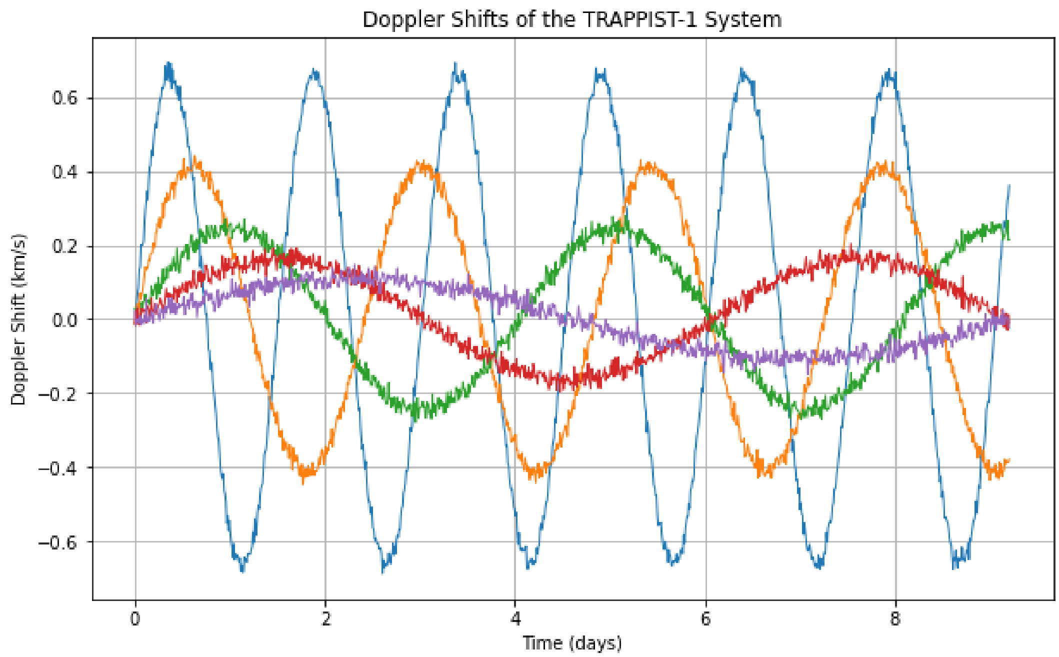
$$r = \sqrt{\frac{(1-\alpha)P}{16\pi\varepsilon_{\text{eff}}\sigma T^4}}$$

Assuming 273 K $< T <$ 373 K, plugging in numbers gives us $r_{\text{inner}} = 0.014$ AU and $r_{\text{outer}} = 0.026$ AU.

(b) (3 points) What are two facts you had to assume about the exoplanets' atmospheres in order to calculate (a)? (*Hint: consider how we defined the habitable zone*)

Solution: We assume TRAPPIST-1's atmospheric pressure is similar to Earth's in order to assume that the edges of the habitable zone are at the melting and boiling points of water on Earth. We also assume that the greenhouse effect on TRAPPIST-1 is similar to that on Earth in order to use the same ε_{eff} value as Earth.

(c) (2 points) The following image shows the Doppler shift data of the planets in the system. Unfortunately, you forgot to label the plot! However, you know that the order of the planets from innermost to outermost is TRAPPIST-1b through TRAPPIST-1f. What planet corresponds to each of the lines? (Name the planet and the color of the line it corresponds to.)



Solution: Planets further away from the star move slower and have longer periods because they experience a weaker centripetal force due to gravity. (The formula for orbital velocity is $v = \sqrt{\frac{GM}{r}}$, derived from setting the centripetal force equal to gravitational force, and the formula for orbital period is described by Kepler's third law.) Since the Doppler shift is due to a planet's velocity towards or away from the observer, planets further away from the star will have weaker Doppler shifts and longer oscillations. Thus, blue is TRAPPIST-1b, orange is TRAPPIST-1c, green is TRAPPIST-1d, red is TRAPPIST-1e, and purple is TRAPPIST-1f.

(d) (2 points) Which of the planets in the TRAPPIST-1 system exhibit 2:3 resonance with TRAPPIST-1f?

Solution: A 2:3 resonance indicates that the other resonating planet would have a period two-thirds the length of TRAPPIST-1f. Given that TRAPPIST-1f is described by the purple data, the only data that fits this description is in red, corresponding to TRAPPIST-1e.

Problem 5

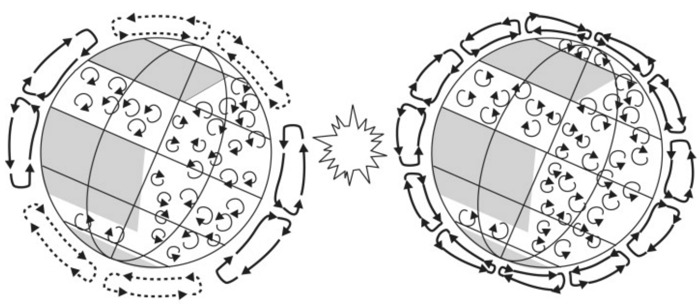
Question	1	2	3	4	Total
Points	3	6	3	8	20 (20 %)

The Cretaceous period (145 to 66 million years ago) had elevated temperatures and a different arrangement of continents that led to a greenhouse state dramatically unlike our modern climate.

1. (3 points) The elevated temperatures occurred both in equatorial and even more so in polar regions. If the average global meridional (north/south) temperature difference was lower, how would you expect average wind strength to compare to the present? Briefly explain why.

   Solution: A more uniform meridional temperature distribution translates to a lower pressure-gradient force, which one would reasonably assume to produce weaker winds compared to present-day winds. This expectation is reasonable but may not entirely be accurate; reality is complicated by changes in other forms of meridional energy transport.

2. Some models suggest that during the Cretaceous, the polar pressure seasonally alternated between high and low. Below is a diagram of atmospheric circulation cells (drawn as cross sections) during two parts of the year (January on left, July on right). Shaded areas represent land, and unshaded areas represent open water.



   (a) (1 point) Of the months January and July, which month do the poles have a surface high-pressure zone? Low-pressure?

   Solution: Low pressure (rising air) in January, high (descending air) in July. The figure is from Hay, 2008; further work since then has revealed that seasonal reversals oversimplify seasonal pressure systems.

   (b) (3 points) The model is based on the assumption the Cretaceous is ice-free. Let's bring our attention to the Arctic (upper pole), then an open-water region surrounded by land. Explain why the Cretaceous Arctic was a high or low pressure zone in winter, and a high or low pressure zone in summer.

   Solution: In the winter, the North Pole would be warmer than the land around it, since the land has a much lower heat capacity and will more quickly radiate away energy. In the summer, it would be cooler than the land, since land heats more quickly than water. As a result, the North Pole contains a surface low in winter and a high in summer.

   (c) (2 points) What characteristic of ice currently allows the Arctic to maintain the polar high in the winter?

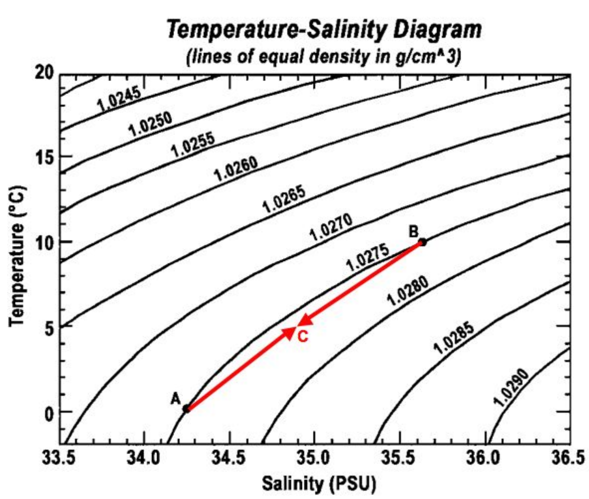
   Solution: Ice insulates air from warmer water, allowing the air to remain cold.

3. (3 points) The small curled arrows in the previous figure represent small eddies that may have governed ocean circulation instead of the highly structured circulation we observe in modern oceans. Using your answer to question 1, explain why structured circulation was less likely to form during the Cretaceous. (*Hint: consider the implications of the changing pressure systems on zonal, or east-west winds.*)

Solution: Wind strength and direction was more variable. In the modern day, established westerlies and easterlies drive gyre circulation, but with the less consistent wind forcing on the ocean surface during the Cretaceous, well-defined circulation structures may not have formed.

4. Global sea level was higher than present day through most of the Cretaceous. Within what we now know as North America was the Western Interior Seaway, the inland sea pictured above.

   (a) (1 point) When sea level further rose, the cooler, fresher water mass from the north mixed with the warmer, saline water mass from the south. Assume for simplicity that our scenario is illustrated by the figure below.



   When the water masses mix, the new parcel:

      A. Upwells

      B. Downwells

C. Neither upwells nor downwells

Solution: Mixing two water masses often produces denser water (known as cabbeling in technical terms). In a plot of temperature vs. salinity, the contour lines for density are concave such that the midpoint between two points on the same contour line will be on the denser side of the contour.

(b) (3 points) Based on your previous answer, are instances of sea level rise in the Western Interior Seaway associated with instances of relatively oxic or anoxic conditions at the sea floor? Describe your reasoning.

Solution: When sea level rises, the seaway receives an influx of water from its northern and southern end. These two water masses mix and downwell. Downwelling water brings relatively oxygenated water from near the surface to depth.

(c) (4 points) Imagine a bed of shale is deposited in the seaway as sea level lowers. Why might you expect the shale to be dark in color? Synthesize conclusions from both parts (a) and (b) in your answer to (c).

Solution: Dark shales indicate a high amount of organic matter, which remains in the shale under anoxic conditions. Previously we saw bottom waters being oxygenated during times of sea level rise due to the mixing of water masses and subsequent downwelling. As sea level falls, however, limited downwelling prevents oxygenated surface waters from reaching the seafloor.